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David Hu

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14. ABSTRACT
An Anton Paarr MCR 501 rheometer was purchased in order to measure rheological properties of biological fluids. Using this machine, we were able to characterize non-Newtonian fluids such as frog saliva, mammalian earwax, feces, blood clots, and fire ants and microgel suspensions..

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Report Title

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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations:

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Project Summary - Grant # 66200EGRI

(Reporting Period: Aug 2015 – Aug 2016)

RI: Rheology as a Tool for Understanding the Mechanics of Live Ant Aggregations, Part 1 and 2

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Objective

An Anton Parr MCR 501 rheometer was purchased in order to measure rheological properties of biological fluids. Using this machine, we were able to characterize non-Newtonian fluids such as frog saliva, mammalian earwax, feces, blood clots, fire ants and microgel suspensions.

Approach

The Anton Paar rheometer is the ideal tool for characterization of biological fluids. Using a cone-plate setup, we were able to accurately measure shear thinning properties in frog saliva, the core result in our recently submitted paper "Frogs use a viscoelastic tongue and non-Newtonian saliva to catch prey". We were also able to measure viscosity of feces, which are often inhomogeneous in nature. The general rheology of feces in mammals leads to non-invasive diagnoses on gastrointestinal health by the duration of defecation, which is in submitted paper "Rectal mucus is critical for defecation."

Relevance to Army

Accomplishments for Reporting Period

- <u>Frogs use a viscoelastic tongue and non-Newtonian saliva to catch prey</u>
  Frogs can capture insects, mice, and even birds using only their tongue, with a speed and versatility unmatched in the world of synthetic materials. How can the frog tongue be so sticky? In this combined experimental and theoretical study, we perform a series of high-speed films, material tests on the tongue, and rheological tests of the frog saliva. We show that the tongue's unique stickiness results from a combination of a soft, viscoelastic tongue coupled with non-Newtonian saliva. The tongue acts like a car's shock absorber during insect capture, absorbing energy and so preventing separation from the insect. The shear-thinning saliva spreads over the insect during impact, grips it firmly during tongue retraction, and slides off during swallowing. This combination of properties gives the tongue 50 times greater work of adhesion than known synthetic polymer materials such as the sticky-hand toy. These principles may inspire the design of reversible adhesives for high-speed application.

- <u>Earwax has properties like paint, enabling self-cleaning</u>

The ear is subject to invaders such as dust, insects, mud and even feces. The secretion of earwax has long been though to protect the ear and remove intruders. We film the motion of the ear canal in humans and measure the rheological properties of earwax of pigs, dogs, cows, and humans. We find that earwax is shear-thinning for all these animals. This ability enables it to cling to the ear in low volumes providing a protective layer to adsorb particles. When large volumes are eventually secreted, the movements of the jaw cause the earwax to flow and fall out of the ear, taking particles with it.

- Rectal mucus is critical for defecation
  Eating food and ejecting waste characterizes nearly all life forms. In mammals, waste ejection is accomplished by an extrusion of feces of various shapes and sizes. Despite the widespread use of fecal form in animal identification and medical diagnoses, the physics of defecation remains poorly understood. In this combined experimental and theoretical study, we investigate the defecation of mammals from cats to elephants. We film defecation at Zoo Atlanta and apply cone-on-plate rheometry to measure the viscosity of mammalian feces. We find all mammals defecate over a nearly constant duration of $T = 12 \pm 7$ seconds (N=22). We rationalize this surprising trend by the mucus lubrication system in the rectum. Larger animals have more feces to expel, but also have a thicker and more slippery mucus layer to facilitate its ejection. Our work may help to inspire non-invasive procedures to diagnose disorders of the intestinal tract.

- Rheology of clotting blood
  We have performed rheology during the formation of a blood clot both with and without an inhibitor. We measured storage and loss modulus in the linear regime during the formation as well as measuring the normal force that the clot applied to the rheometer. We found that while the inhibitor did not change the moduli of the clot it did change the normal force that the clot was able to apply. The inhibitor affects the forces that the platelets can apply but does not change the formation of the physical network that makes up the clot. Its effect on the platelet force is seen in the change in the normal force with inhibitor.

- Activity cycles in fire ant aggregations
  While we are not able to control the internal energy level of the fire ants, we have watched them over long periods of time to see if it changes naturally and if we can detect it. What we have found is that the normal force that the aggregation applied while in the rheometer is related to the activity level of the aggregation. We can then track the activity level in time by monitoring the normal force. We found that fire ant aggregations go through cycles of activity. There are regular periods where they are inactive punctuated by short periods with high levels of activity.

Microgel suspensions

We have performed rheology on dense microgel suspensions. These are comprised of colloidal hydrogel particles that are able to swell and deswell depending on ambient variables like temperature, salt concentration or pH. We use these systems to address glass formation and jamming. The experiments typically consist in doing oscillatory rheology in the linear regime, as well as non-linear steady-state rheology. In this way we are able to obtain independent estimates of the structural relaxation time of the suspension. We find this time exhibits an apparent divergence followed by a leveling off, which reflects the compressive nature of the particles. These studies address how this compressibility affects formation of disordered solids.

Collaborations and Technology Transfer

Resulting Journal Publications During Reporting Period

- Tennenbaum, M., Liu, Z., Hu, D. & Fernandez-Nieves, A. Mechanics of fire ant aggregations. *Nature materials* (2016).
- Myers, D., Qiu, Y, Fay, M., Tennenbaum, M, Chester, D, Cuadrado, J, Sakurai, Y, Baek, J, Tran, R, Ciciliano, J, Ahn, B., Mannino, R. G., Bunting, S. T., Bennett, C., Briones, M., Fernandez-Nieves, A., Smith, M. L., Brown, A. C., Sulchek, T. & Lam, W. A. Single-platelet nanomechanics measured by high-throughput cytometry. Nature Materials (2016).
- (in preparation) Tennenbaum, M., Hu, D.L., & Fernandez-Nieves, A. Dynamically reconfigurable mechanical properties of fire ant aggregations.
- (in preparation) J. S. Hyatt, A. Fernandez-Nieves, Avoiding the glass transition in dense suspensions of ionic microgels.
- (under review) A. Noel, H.Y. Guo, M. Mandica, & D. L. Hu. (2016) Frogs use a viscoelastic tongue and non-Newtonian saliva to catch prey. *Journal of the Royal Society Interface*.
- (submitted) P. Yang, M. LaMarca, C. Kaminski, & D. L. Hu (2016) Rectal Mucus is critical for defecation

Presentations

- A. Noel, H. Choe, J. Ha, A. Fernandez-Nieves, J. Mendelson, D.L. Hu. “To catch a fly: Viscosity and elasticity-based prey capture by frog tongue projection.” ACS Colloids Symposium, 2014.
- A. Noel, C. Wagner, G. McKinley, J. Mendelson, D.L. Hu. “The role of extensional viscosity in frog tongue projection.” Applied Physics Society Division of Fluid Dynamics annual meeting, 2014.
- A. Noel, D.L. Hu. “To catch a fly: The role of saliva adhesivity during prey capture in frog tongue projection.” Society for Integrative and Comparative Biology annual meeting, 2015.
- Z. Zachow, A. Noel, D.L. Hu. “Earwax has properties like paint, enabling self-cleaning.” Society for Integrative and Comparative Biology annual meeting, 2017.
- P. Yang, D. Dao, R. Lehner, D. Hu, “The hydrodynamics of defecation” Annual Society for Integrative and Comparative Biology Conference, West Palm Beach, FL, Jan 3-7, 2015
- P. Yang, D. Dao, R. Lehner, M. Tennenbaum, A. Fernandez-Nieves, D. Hu, “The hydrodynamics of defecation” American Physical Society’s Division of Fluid Dynamics Annual Meeting, San Francisco, CA, Nov 23-25, 2014

Graduate Students Involved During Reporting Period

- Patricia Yang (PhD, current)

- Alexis Noel (PhD, current)

Awards, Honors and Appointments

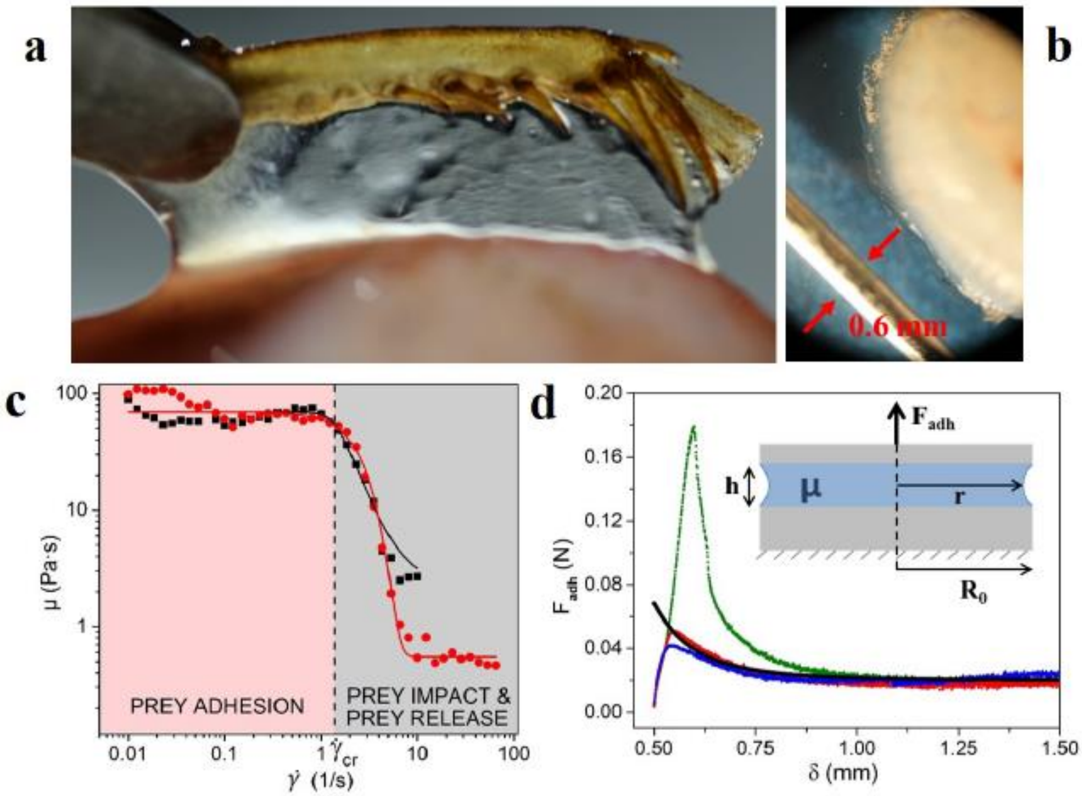

Figure 3: Saliva properties. (A) A cricket leg is retracted from the frog tongue. (B) Frequency sweep test of frog saliva. Black and red symbols denote experiments, solid lines the Carreau-Yasuda theoretical model. (C) Separation forces for frog saliva sandwiched between two parallel plates as shown in inset. Blue (□), red (□) and green (□) symbols denote 3 experimental trials. The black line denotes the Stefan theory.

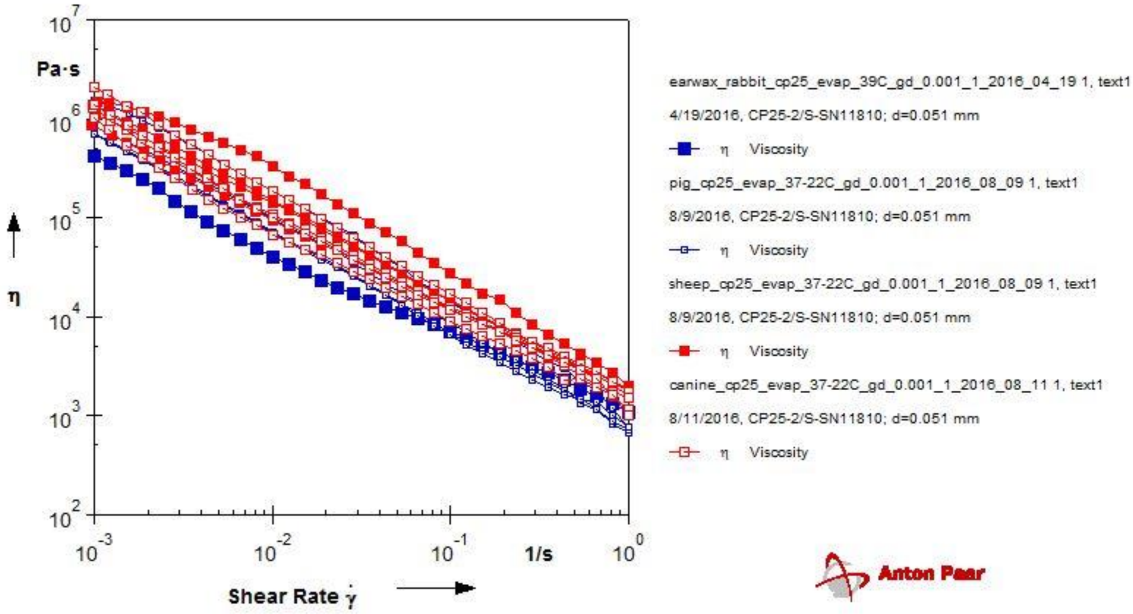

Fig 1: Earwax viscosity same across species